COMPUTER-AIDED DESIGN (CAD) OF TVRO EARTH STATIONS

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ABSTRACT

Not long ago the process of designing a TVRO earth station was relatively uncomplicated. Consider that there were a few manufacturers offering a few products to a few prospective customers. Economy was secondary to performance since all earth stations were very expensive and since very strong signals were necessary because of equipment limitations and projected use. Of course the situation at present is much different. The amount of equipment on the market has increased spectacularly. The costs have fallen as competition has increased and as the equipment is manufactured in larger numbers to accommodate a much larger market. Satellites have proliferated, become more powerful and more closely spaced. In a word the design of a modern TVRO earth station is now "complicated".

Faced with these increasing pressures on our engineers and mindful of the expanding market opportunities the decision was made to enter the modern age when it comes to earth station design. We committed ourselves to Computer-Aided Design. In this way we would form a powerful design team by combining best aspects of our talented engineers with the speed and agility of our mainframe computers.

The importance of this CAD package to the CATV operator or engineer is twofold: 1) confidence that earth stations resulting from the use of this CAD package are highly appropriate and cost-effective and 2) the reports resulting from this CAD package are available to the industry.

This report summarizes the decisions made while developing our earth station CAD package. A sample design session illustrates the effectiveness, flexibility and speed of the CAD process. The enhancement of designer creativity is pointed out. Many of the details concerning the performance calculations and the assumptions upon which the calculations rest are outlined. Finally, a few thoughts are given on the future usefulness of this CAD package in the 2-degree spacing environment.

THE NEED

Our design engineers' offices used to contain bookshelves crammed with thick notebooks containing satellite information, volume after volume of manufacturer's specification sheets and folders of various technical reports detailing the computations necessary to design and predict the performance of a TVRO earth station. The design process was cumbersome, error-prone and slow. There was no easy way to ensure that the data used by each of the engineers was up-to-date or even the same. A quick performance estimate could only be produced by the 'old-hands' who could rely heavily on intuition based on their past experience. Armed with their unique (and often cryptic) notes, these experienced engineers could pretty quickly converge on a reasonable design and, even more importantly, could usually spot a probable error in one of the calculations soon enough to avoid wasting valuable time.

But, what was sorely needed was a way to capitalize on this design intuition, a way to allow our designers to see the performance estimates of several systems at the same time for easy comparison and a way to encourage design creativity by relieving the engineers of the laborious calculations and endless searching for data. The need was for a means by which an optimum earth station system to be quickly converged upon by an engineer new to the business. Simply stated, we saw a need for a Computer-Aided Design (CAD) package which would allow our engineers to use our mainframe computers as a design tool. Since we could not find the necessary help from commercial software vendors, the decision was made to produce our own programs. Our philosophy was that these programs would be menu-driven (that is, would present a list of operator choices when appropriate) and user-friendly (that is, the users would not need to know anything about computers or programming to use these CAD programs). Our goal of a man-machine design partnership for the TVRO earth station design process is shown in figure 1.
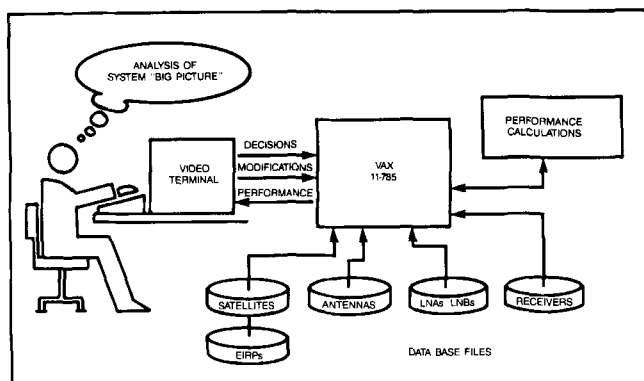
Figure 1. CAD Man-Machine Partnership

As with all CAD routines, success would hinge on the ease of use and the ability to capitalize on the inherent strengths of the human designer and the computer. The engineer would provide the raw data about the site and an understanding special factors important to the customer and would make the necessary design decisions. The computer would be the custodian of the miriad data on equipment, satellites and standards, which must be available. These data would be stored in database files representing digitized versions of the packed bookshelves formerly used. Each of our engineers would thus have immediate access to the most up-to-date and reliable information. A database management program would be used to maintain this database, allowing the manager to add, delete or modify any record at any time. The computer would perform all necessary calculations since it is very fast and highly precise. The computer could now instantly provide the engineer with reliable information and projected signal qualitites.

The engineer would capitalize on the machines's strengths of speed and data-storage. But for the man-machine partnership to function at its best, the superior analytical abilities of the engineer must be brought to bear on the design of the system. The Computer-Aided Design programs must be highly interactive, providing considerable flexibility to the design engineer so as to promote and not hinder his creativity. The engineer is called upon to evaluate the performance of the system under design. Until the performance is satisfactory, the engineer must be afforded complete latitude in deciding on what system changes should be made. After these modifications have been made the computer will instantly reevaluate the system performance and allow the engineer to analyze the effects of the modifications. This man-machine interaction continues until the engineer is satisfied with the resulting performance.

The step-by-step decisions are always left to the engineer since he can understand and interpret many subtle and seemingly unrelated interactions which that computer cannot. For example, the engineer can more easily weight such factors as cost, unique site situations, interfacing with

equipment already in place, customer idiosyncracies and the like. The human mind is much better at being able to see how each detail fits into the "big picture". A successful CAD program is a powerful tool for the engineer to use, it cannot replace him.

AN OVERVIEW

A clearer understanding of the CAD partnership can be obtained by following along with an example design session which is presented here. The next part of this paper will summarize the details of the assumptions and algorithms used in the programs. The components which the CAD system recognizes as comprising a TVRO earth station are shown in figure 2. As can be seen, this system includes the satellite source of the downlink microwave signals and produces the baseband output which can then be further processed by the headend equipment and distributed.
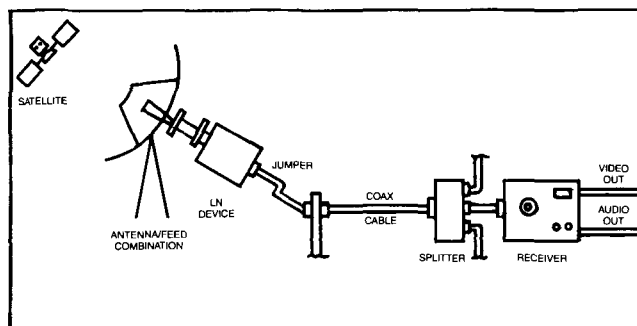

Figure 2. Earth Station System Components

The customer provides the information necessary to begin the CAD process; that is, the site's latitude and longitude, the name of the satellite(s) which may be accessed, and the intended use of the signals that will result from the receiver. The latter information gives the engineer a feeling for the levels required to

Applications Engineering
EARTH STATION CAD Version 1.0
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1. Customer: *NCTA TEST*
2. Location: *ATLANTA, GEORGIA*
   latitude [D,M,S]: *34,10,15*
   (N) or S: *N*
   longitude [D,M,S]: *84,20,5*
   (W) or E:

Figure 3. First CAD Screen
(NOTE: The *ITALICS* represent input to CAD)

produce acceptable results. As soon as the engineer calls for the Earth-Station CAD program, a screen similar to figure 3 appears on his video terminal. The engineer enters the customer's name, site location and latitude-longitude coordinates in the appropriate locations according to the prompts.

When first started, the CAD program has the engineer assemble a preliminary earth station system. These first-system components are chosen in an order roughly opposite to the signal flow; that is, working from the receiver "backwards" to the satellite. Therefore, the engineer first chooses one receiver for the system. The engineer's choices reflect the goal of total design freedom. He can decide to choose any S-A receiver by simply entering the model number. If this is done, all of the necessary data for later calculations are read by the computer from an internal database file which is, in a sense, a digitized version of our specification sheets. However, the engineer can also choose to enter the necessary receiver data, guided by prompts on his terminal, effectively defining any receiver what-

soever. By this means, the product of another vendor can be tested, or the designer can experiment with any "what if" scenario. Either way the receiver data necessary for performance calculations are now stored in the computer's memory. Figure 4a approximates the screen seen by the designer choosing an S-A product and 4b shows the prompts used if the designer chooses to define a receiver.

Next, the engineer is prompted to provide an estimate of the total dissipative and dividing loss, in dB, between the LNA (or LNB) and the receiver (see either of the figures 4). This parameter would include the coax cable runs, the jumpers and splitters that may be necessary. On the first run, a typical value is often used. Later, after the system component choices have been narrowed by successive design runs, the effect of more or fewer splitters or of more or less expensive cable can be carefully analyzed by the engineer.

Working backwards, the next system component that must be chosen is the Low Noise (amplifying) Device. The computer program can use either an LNA with a block-downconverter at the receiver or an LNB delivering an amplified and downconverted frequency band to the receiver. Flexibility of design is provided by allowing the engineer to use the S-A LN Devices which would interface with the receiver already chosen or by allowing him to define the parameters of any LN Devices. These choices can be be seen in the menu shown in figure 5a. If S-A LNDs are to be used the computer will obtain the device parameters by searching its LND files. On the other hand, if the designer chooses to define his own LNDs the computer uses the prompts shown in figure 5b to obtain the required data. In either case the program stores the specifications for up to six LNDs thereby allowing for easy comparison of LNDs differing in gain and/or in noise temperature.

3. Receiver: _6650_____ [mod #, "DATA", "HELP"]

4. estimated loss: _15_ dB

Figure 4a. Receiver Choice by Model Number

3. Receiver: _DATA_____

noise figure =	_____	dB
IF noise BW =	___·___	MHz
C/N threshold =	___·___	dB
input lo freq =	_____	MHz
hi freq =	_____	MHz

4. estimated loss: _____ dB

Figure 4b. Receiver is User Defined

5. LNDs: type (Y) to Use series _360_____ LNDs?
         2 to enter LNA data
         3 to enter LNB data
         4 to change receivers [(Y),2-4]

Figure 5a. LND Data Menu

5. ENTER LNAs data: (LNA frequency bands will match
those of satellite and receiver)
gain   noise T

LNA 1:___·___ dB _____ K
etc.

Figure 5b. Example Screen for Entering LND data

6. Satellite Name: *DATA*_____
ENTER: orbit longitude   = _____
[(W) or E]?
median dn freq = __·__ GHz
EIRP from site = __·_ dBW(est)

Figure 6b. Satellite Data Entered

The name of the satellite for which the system performance will first be predicted is now entered as seen in figure 6a. The program will determine the performance of the earth station for signals originating at one satellite at a time. This is not a limitation however, as the satellite can be changed as many times as desired thus simulating the moving of the antenna from one satellite to another. Computer records on every satellite worldwide capable of C or Ku band video programming have been included in the database. However, as in the past entries, the operator is free to define his own satellite, prompted as shown in figure 6b, and can therefore explore any "what-if" problem that comes to mind. The elevation angle of the satellite is immediately determined for the site. Additionally, for the eight most popular satellites visible from CONUS, we have digitized the typical footprints from which the computer can obtain a very good estimate of the EIRP of the satellite viewed from the site's location. Otherwise, the engineer must (or may at any time) provide an estimate of the satellite's EIRP.

The last system components chosen by the engineer are the antenna/feed combinations. The program treats the feed as a part of the antenna, and therefore, the antenna data are always referenced to the feed port. There is virtually no limit to the number of antennas that can be entered for any computation run. To maintain the concept of complete design freedom, the choice alternatives are presented as a menu as seen in figure 6a. It is common for our engineers to have the computer include every S-A antenna on record for the first run in order to get a quick idea of a reasonable antenna size. Choosing menu items "A" or "S" (see figure 7a) sends the computer to its antenna files to obtain the necessary data. Again notice that menu option "D" allows for total design flexibility. An engineer choosing "D" is prompted to enter the necessary antenna data as shown in figure 7b. Antenna noise temperatures are either interpolated from the S-A records for the proper elevation angle or must be entered by the engineer. Noise temperatures are redefined whenever the satellite (and therefore the elevation angle) is changed.

6. Satellite Name: *GALAXY 1*___ [name, "DATA", "HELP"]

orbit longitude   = 134.0 W
median dn freq = 3.95 GHz
EIRP from site = 35.18 dBW est? [(Y), N]

Figure 6a. Satellite Chosen by Name

7. Dishes: type A to use' ALL S-A dishes
S to use SOME S-A dishes
D to enter dish DATA   [(A),S,D]

Figure 7a. Antenna Choice Menu

Figure 7b. Screen Allowing Antenna Data Entry

ENTER data for C band dishes:
   size gain ,   24 deg elevation
     (m)   (dBi) noise temp. (K)
DISH 1: __.__   ___.___   _____.
etc.

Finally, the engineer is presented with a menu of possible choices for video format to be decoded by the receiver (figure 8). The formats are named using by the color encoding that is usually associated with each. Here for example, "NTSC" denotes video signals using: 525-line, CCIR standard M, 60 Hz, 4.2 MHz bandwidth and with NTSC color modulation. Therefore, menu choices #1 to #4 cover the vast majority of video transmissions in use. The programs provide the video format parameters required in the calculations. Menu options #0 and #5 enhance flexibility by allowing video S/N calculations to be omitted or by allowing user definition of any other video format. Thus, other formats such as B-MAC or half-transponder conference video are effectively handled.

8. Video S/N option: 0 NO VIDEO S/N calculations
                       1 NTSC   525, 4.2 MHz
                       2 PAL I   625, 5.0 MHz
                       3 PAL B/G 625, 5.5 MHz
                       4 SECAM   625, 6.0 MHz
                       5 USER DEFINED video format
                         [(0)-5]

Figure 8. Menu for Video Format to be Used in S/N Calculations

At this point the computer takes over and does all of the necessary calculations to predict the performance for every possible combination of receiver-LND-antenna which can be assembled using the equipment that the engineer has entered. The details of these calculations are presented in the next part of this paper. The results of the calculations are stored in memory and are available

to the engineer at his convenience. Normally a preliminary summary of the system performance predictions is requested by the engineer and scrutinized on his terminal.

Now the real man-machine teamwork begins. The engineer is now presented with a menu that allows any modification to be made on the system under review (see figure 9). Different receivers can be tried, different antennas, LNDs, cable loss, video format, satellite. After each change (or whenever he likes) the designer can tell the computer to recalculate the system performance predictions and can immediately see the effect of the change(s). This iteration of modification and recalculation can continue for as long as necessary; however, we find that even inexperienced designers quickly converge on an optimized system.

9. CHANGES? 0 No changes - EXIT CAD
              1 another customer
              2 another site, this customer
              3 change receiver
              4 change loss estimate
              5 change LNDs
              6 change Satellite
              7 change dish(es)
              8 change video format
              9 to see a performance report [0-9]

Figure 9. Change Menu Allowing Any Series of Alternations Until Performance is Satisfactory

It is interesting to note that even the satellite can be changed. Normally, this is done after a system-optimization has been done on the satellite of primary interest. This feature allows the designer to "point" the system at any satellite visible from the site and obtain a prediction of the system performance instantly. Also, many internal checks are built into the program to prohibit invalid combinations in the earth station system. All system components are constantly checked to ensure frequency compatibility. Systems resulting in C/Ns below the receiver threshold are flagged so to be immediately apparent to the operator.

So the key to this and all successful CAD systems is the concept of a man-computer partnership that capitalizes on the strengths of each. The human partner brings a clear view the the overall plan, and with experience has an intuitive feel for the system that cannot be programmed. The man has the fantastic flexibility of the mental processes that allows for unusual or unique circumstances to be easily dealt with. It is also easy for the human to compare the performance predictions of many systems at a glance, to quickly discern meaningful trends and cull "blind alleys".

On the other hand, the computer is a faithful and tireless keeper of the miriad data that must be be available to the designer. The computer can perform the tedious and complex calculations instantly and unerringly and can store these results for access at the engineer's convenience. But the success of the design still rests on the decisions made by the engineer; however now those decisions can be made based on much more data. You can see that the CAD program has not replaced the design engineer, but has instead freed him of the tedium and allowed for more creativity and effiency.

DETAILS OF THE CALCULATIONS

1. Satellite Trignometry:
   The computer makes the following calculations immediately after the satellite data has been stored. These formulas are based on the assumptions of a perfectly spherical smooth earth of radius 3957 miles, satellites in perfectly circular geosynchronous orbits at an altitude 22245 miles above the earth's surface. Northern latitudes and eastern longitudes are positive, southern latitudes and westerly longitudes are negative.

   The great-circle angular distance, θ, from the site to the satellite sub-point is first determined using the following formula. If $\theta > 81.3$ then the operator is informed that the satellite is below the local horizon and another satellite must be chosen.

   $$\theta = \cos^{-1}(\cos \emptyset \quad \cos a) \qquad (1)$$

   where $\emptyset$ = site-satellite longitudes
    a = site latitude

   Local terrain variations or unusually low elevations need to be carefully considered by the designer.

   The program for visible satellites proceeds by calculating the azimuth angle (A), and elevation angle (E), and the distance in miles (S), for a line-of-sight path from the site to the satellite. The following algorithms are used:

   $$A = \tan^{-1}\left[\frac{\tan \emptyset}{\sin a}\right] + \left[180^\circ \quad \begin{array}{l}\text{if in northern}\\ \text{hemisphere}\end{array}\right] (2)$$

   $$S = \sqrt{R^2 + (R+h)^2 - 2R(R+h)\cos \theta} \qquad (3)$$

   $$E = \cos^{-1}\left[\frac{S^2 + R^2 - (R+h)^2}{2RS}\right] - 90^\circ \qquad (4)$$
   (4)

    Where $\emptyset$, a, θ see (1) above
    R = 3957 miles
    h = 22245 miles
    S = line-of-sight distance, miles

2. Satellite Eirp
   The program searches through the files of digitized footprint tables attempting to find a record for the requested satellite. EIRP estimates for recorded satellites are found by using a standard bivariate interpolation on the table. The accuracy of the interpolation is better than the footprint data themselves thus introducing no additional uncertainty.

   The digitized footprints were determined from the EIRP contour maps released by the satellite operators. There is only one record per satellite, so the digitized EIRPs are assumed to represent typical values for a saturated transponder. For this reason, the performance estimates obtained are typical for the satellite. For atypical situations the engineer can override the computer estimate of the EIRP and assign a different value.

3. System Noise Temperature and System G/T
   The first series of performance calculations determines the system noise temperature and then uses that result to determine the figure-of-merit (G/T). Recall that these calculations are performed successively on every possible combination of antenna, LND and receiver entered by the engineer. The formulas used are:

   $$t_s = t_{ANT} + t_{LND} + \frac{t_{CABLE}}{g_{LNC}} + \frac{t_{RCVR}}{g_{LNC}\, g_{CABLE}} \qquad (5)$$

   where t_s = system noise temperature at feed flange, K

   t_{ANT} = antenna noise temperature K

   t_{LND} = LN device noise temperature, K

   $$t_{CABLE} = \left[10^{LOSS/10} - 1\right](290), K$$

   $$t_{RCVR} = \left[10^{N.\ FIG/10} - 1\right](290), K$$

   g_{LND} = LND gain ratio

   g_{CABLE} = cable loss ratio

   $$G/T = G_{ANT} - 10 \log t_s \qquad (6)$$

   where G_{ANT} = antenna gain (dBi)

   Several points should be emphasized at this point. First, the system noise temperature is referenced to the input flange on the LN device. Second, the antenna and feed horn are treated as a unit; thus the antenna's gain (dBi) and noise temperature are referenced to the feed output port. The noise temperatures for the antennas and the LNDs and the noise figures for the receiver have been stored in memory after being read from

internal files or input by the engineer. All
cable, splitters, etc. are considered to be at
a temperature 290 K. The calculations also
suppose that the VSWR is better that 1.3:1 and its
effect can be neglected. Lastly, the antenna
gains used in this calculation are specified at
mid-band (3.95 GHz for C-band and 11.95 GHz for
Ku-band). For some of the other Ku-band frequency
schemes (Telecom 1 for example), the gain of the
antennas are revised according to the formula:

$$G = G_{nom} - 20 \log \left[\frac{f}{f_{nom}}\right] \qquad (7)$$

where the antenna efficency is assumed not to vary
appreciably. No changes are made to the antenna
noise temperatures since it was felt that the
difference due to the frequency shift was less
that the variation of noise temperature among
different samples of the same antenna.

4. IF C/No and C/N

The next receiver IF carrier-to-noise
power-density (C/No) and the C/N are found as
outlined below. Note that no performance margin
was included in the downlink calculations.
Degradation allowances are always left up to the
engineer since he has a better picture of what may
be appropriate for each site. Again, recall that
the necessary variables have been previously
determined have been stored in memory.

$$L_p = 96.6 + 20 \log f + 20 \log S \qquad (8)$$

$$C/N_o = EIRP - L_p + G/T + 186.6 \qquad (9)$$

$$C/N = C/N_o - 10 \log B_{IF} \qquad (10)$$

where L_p = free space path loss (dB)
f = satellite median downlink
frequency (GHz)
S = (see formula 3)
EIRP = satellite transponder EIRP
186.6 = Boltzman's comst
G/T = (see formula 6)
B_{IF} = effective IF noise bandwidth
(MHz) of receiver

5. Baseband Video S/N

The last of the system performance parameters
to be determined is the (optional) baseband video
signal-to-noise ratio, S/N. The algorithm used is:

$$S/N = C/N_o + 20 \log \left[12 \quad F\right] - 30 \log B_n \qquad (11)$$

where C/N_o = (see formula 9)
F = half the peak-to-peak
deviation produced by
the luminance signal
B_n = noise bandwidth of the
weighted baseband filter
function

The computer is programmed with the basic data
for the four most common video format standards.
These data are based primarily on CCIR Rec. 421
and assume a weighted baseband filter-function,
however the user is free to define any format he
wishes.

THE FUTURE

It is important to realize that the CAD
programs described so far have been found
extremely valuable and are used on a daily basis
by our engineers; however, we do not consider the
program development at an end. The actual pro-
grams themselves are written in a modular form so
that enhancements and updates can be easily made.
Many minor and major modifications have been made
based on the suggestions of our users. As our
engineers gain familiarity with the computer as a
design tool they are encouraged to suggest new
uses.

As of this writing, the decision is that our
next major effort will be to expand the capabili-
ties of the performance calculations to include
a detailed analysis of the carrier-to-interference
levels due to the neighboring satellites. Some
groundwork has already been done towards that
end. We expect to be able to use the computer and
our already extensive satellite database files to
compute very good predictions of the C/I levels
unique to each site and orbital position. No
longer will we have to make rule-of-thumb esti-
mates of the C/I. The thrust for this next
addition is, of course, the 2-degree spacing rule
passed by the FCC. As the 2-degree rule is
implemented we expect that this part of the CAD
package will become very important.

Considerable additional information regarding the calculations outlined above can be found in the following sources:

formula (1) - (4): F.M.Fonda; "Earth Station Geometry"; Communications Symposium '83; 11/83.

formula (5): J. S. Hollis; "Noise Temperature and G/T of Satellite Receiving Systems"; Communications Symposium '83; 11/83.

formula (6): J. Cook; "Earth Station G/T"; memo to J. Levergood; 10/15/75.

formula (7): R. Barker and J. Friesz; "Earth Station Antennas, RF Considerations"; Communications Symposium '83; 11/83.

formula (8) - (10): "Satellite Link Analysis"; Communications Symposium '83; 11/83.

formula (8) - (10): J. Hart; "Satellite Receiver System Presentation"; Earth Station Technology Conference; 7/76.

formula (11): T.M. Straus; "The Relationship between NCTA, EIA and CCIR Definitions of S/N"; IEEE Transactions on Broadcasting, Vol: BC-20, No. 3; 9/74.

formula (11): L. Clayton; "FM Television S/N"; IEEE Transactions CATV, Vol: CATV-1, No. 1; 10/76.

general: S. Havey; "Update of CATV Data Book"; memo to Bob Mauney; 2/28/84.